

# Study of dynamic and static routing for improvement of the transportation efficiency on small complex networks

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## Abstract

In this paper, we are interested in optimization of complex network without changing average connectivity or total network capacity. The focus is on efficient routing. The routing strategies are compared using two generic models, i.e., Barabási-Albert scale-free network and scale-free network on lattice, and academic router networks of the Netherlands and France. The nodes without buffers are considered, so, if congestion occurs, packets will be dropped. We propose a dynamic routing algorithm which automatically extends path of the packet before it arrives at congested node. Simulation results indicate that proposed routing strategy can further reduce number of dropped packets in a combination with the efficient path routing proposed by Yan et al. [Phys. Rev. E 73, 046108 (2006)].

**Keywords:** complex networks, traffic congestion, bufferless node, routing

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## 1. Introduction

Complex networks are important for functioning of the modern society. To ensure a free, uncongested traffic flows on the complex networks is of great interest. Intuitively, the traffic congestion could be largely reduced or completely avoided with a very large average degree of connectivity and node capacity for data packet delivery, that require high cost. The capacity of nodes to deliver information cannot be infinite. Also, upgrading the infrastructure is often not economically feasible [1, 2]. The performance of the communication systems can be upgraded by implementing the more appropriate routing protocols without changing the underlying network structure [3–17], which is more realizable in the practice. Such work presents two difficulties. First, finding out the optimal strategies for traffic routing on defined network structure. Second, it is hard to draw general conclusions from computed results due to the variation of the real network topologies. A number network models is introduced in the last two decade [18, 19]. A particular class of models is dedicated to networks embedded in the space [20]. Here we are interested in evaluating the models for representation of the spatially constrained networks, both in terms of the length of links and the extent of the network (i.e., regional optical backbones, academic networks). As examples of the the real-world networks, we analyze information flow and routing strategies on the national research and educational networks (NRENs) of France [21] and the Netherlands [22]. Since increasing speed of network interfaces raises an important question concerning the size of buffers, increased latency, complexity and cost, our intention is to produce a relatively simple methodology for evaluating routing strategies for the optical networks with limited buffering capability or without optical buffer [23–30]. In previous studies, the node buffer size in traffic-flow model is set as infinite [3–16].

The shortest path routing is widely used routing strategy in praxis (by "shortest" we mean the path with smallest number of links) [31]. However, in the shortest path routing strategy load distribution is not homogeneous, the majority of the shortest paths pass through the nodes that are highly connected, while other nodes carry much less traffic [32]. Yan et al. [5] presented an approach to redistribute traffic load in highly connected nodes to other nodes using link weight. An improvement is achieved through a targeted traffic redistribution from the most congested nodes. As result the congestion is reduced at expense of slight increase of the total path length and traffic. We compare this routing strategy with a dynamical routing strategy. The dynamical routing strategy improves the control of the

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congestion in the heavily loaded nodes by dynamically returning packet one step back. In this way, the dynamical strategy uses the redundant capacity of the links in network to temporarily store information, until congested node capacity is free. Further, we test a possibility of combining dynamical and static routing strategy.

The paper is organized as follows: in Sec. II we introduce generic scale free model and scale free model on lattice and compare their network characteristics. In Sec. III, the information flow model and measure of system performance are introduced. Static and dynamic routing strategy are described in Sec. IV and the performance of dynamical and static routing strategy is analyzed in Sec. V.

## 2. Network models

In this work, we compare topological network characteristics Barabási and Albert scale free model [18], scale free model on lattice [20] and national research and educational networks (NRENs) of France and the Netherlands. Barabási and Albert observed an existence of a high degree of self-organization characterizing the large-scale properties of complex networks [18]. They have introduced a model of scale free networks based which had two key elements: probability that a new node connects to the existing nodes is not uniform and there is a higher probability that it will be linked to a node that already has a large number of connections. Thus, Barabási-Albert (BA) scale free network model is formed in a series of steps in which new nodes are incorporate into the network. Algorithm is starting with a small number ( $N_0$ ) of nodes, and at every time step new nodes with  $m$  connections are added that link the new node to  $m$  existing nodes in the system. To incorporate preferential attachment, the model assumes that the probability of the new connection with the node  $i$  depends on its connectivity  $k_i$  and equals  $P(k_i) = k_i / \sum k_j$ . After a few algorithm steps, distribution of number of links per node takes scale free form  $P(k) \sim k^{-\lambda}$ . Exponent  $\lambda$  in this model depends on size of initial network. In this work, for  $N_0 = 3$  and  $m = 2$ ,  $n = 61$  algorithm steps are preformed. Obtained network consists of  $N = 64$  nodes with  $\lambda = 2$ . Also, the obtained network degree distribution corresponds well to the NRENs of France and the Netherlands, cf. Fig. 1(a)).

However, the real-life networks are embedded into the geographical space and constrained by cost of the link between nodes. In scale free model on lattice (SFL), cf. [20], algorithm starts with a set of nodes that are identified with the set of lattice vertices in an  $N \times N$  square and we define the lattice distance between two nodes to be the minimal number of "lattice steps" separating them in the regular lattice. In this model network nodes are randomly assigned with the number of links ( $k$ ) according to scale-free distribution  $P(k) = Ak^{-\lambda}$ ,  $2 < k < K$  and connected to its closest neighbors. Therefore, exponent  $\lambda$  is a model parameter of explicitly use. We have used  $\lambda = 2$  obtained from the connectivity distribution of NRENs of France and the Netherlands, cf. Fig. 1(a). The choice of model parameter  $\lambda$  is also in accordance with scale-free distribution obtained with BA model. Normalization constant is  $A \sim (\lambda - 1)m^{\lambda-1}$ , for large  $K$ .

At the first glance the most efficient mean to transfer information through the network is along the shortest paths. Therefore, it is useful to represent the shortest path length in the network from the node  $i$  to the node  $j$ , with  $d_{ij}$  and calculate corresponding distribution of the shortest path lengths. The network diameter  $D$ , can be defined as the maximal length of the shortest path between any two nodes in the network ( $D = \max d_{ij}$ ). The small network diameter means that packets transmitted through the network, travel from one node to another quickly along the shortest path. As result the possibility of loss due to the congestion of the transmitting nodes is reduced. From Fig. 1(b), one can observe that the path length distribution of the BA scale-free network does not match NRENs well. This is not surprising, since in the BA scale-free model the Euclidean distance between nodes is irrelevant. For the version of scale free network on lattice, the model has desirable properties in terms of paths length. Both NRENs in this study had network diameter  $D = 11$ . Scale free network (BA) generation algorithm generates networks with considerably smaller network diameters  $D = 6.84$ . Average network diameter obtained for scale free on lattice model (SFL) is  $D = 10.81$ , and compares well with diameters of two NRENs.

The communication of two non-adjacent nodes, i.e., node  $j$  and node  $k$ , depends on the nodes belonging to the paths connecting the nodes  $j$  and  $k$ . Consequently, a measure of the relevance of a given node can be obtained by counting the number of geodesics going through it, and defining the so-called node betweenness. More precisely, the betweenness  $b_i$  of the node  $i$ , sometimes referred to also as load, is defined as [32, 33]:

$$b_i = \sum_{j,k \in N, j \neq k} \frac{n_{jk}(i)}{n_{jk}} \quad (1)$$

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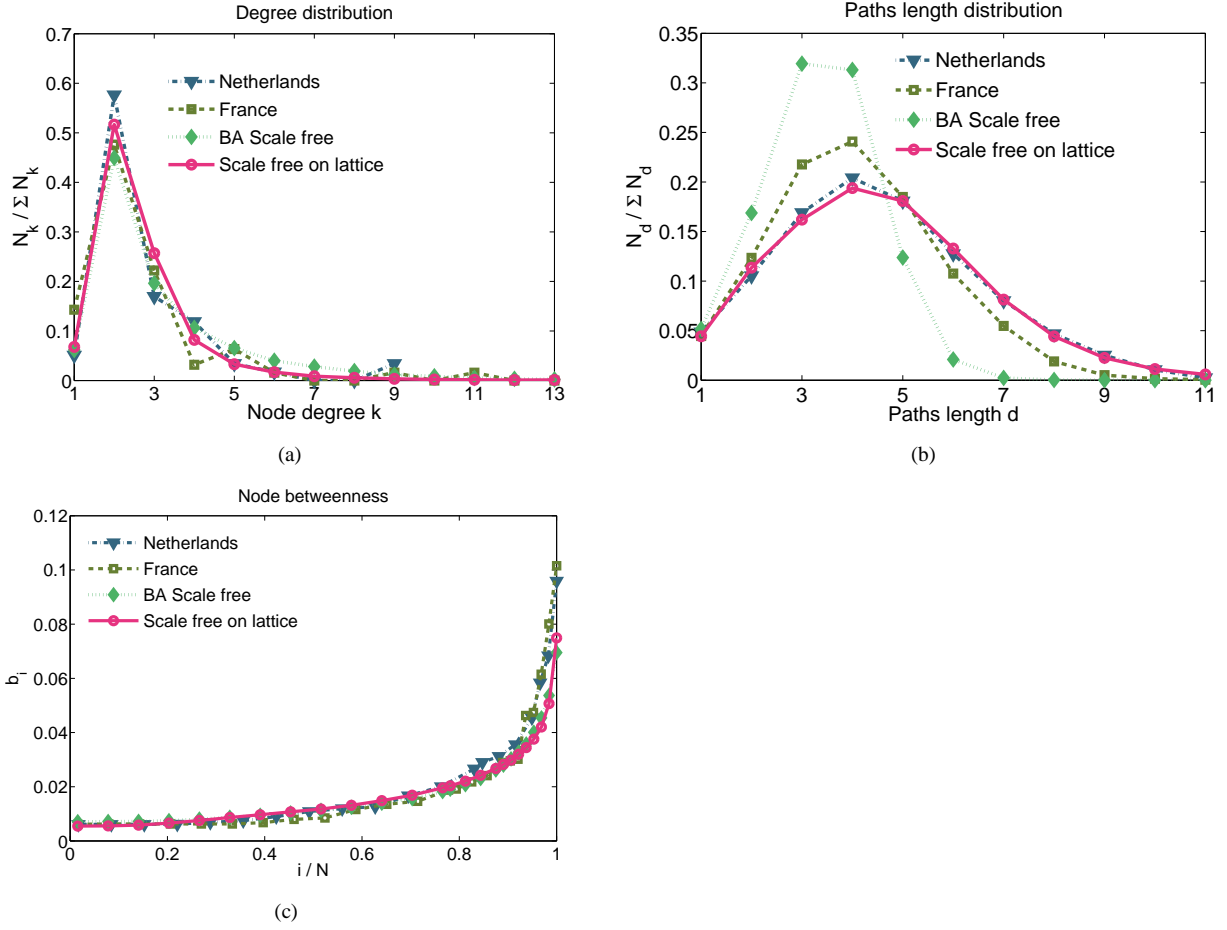


Figure 1: Topological characteristics: (a) degree distribution; (b) length of path probability density function; (c) distribution of node betweenness for NRENs of France and Netherlands, BA scale free network ( $N = 64, m = 2$ ) and scale free network on lattice ( $N = 64, \lambda = 2$ ).

where  $n_{jk}$  is the number of the shortest paths connecting  $j$  and  $k$ , while  $n_{jk}(i)$  is the number of the shortest paths connecting  $j$  and  $k$  and passing through the node  $i$ . The betweenness distribution for different networks is shown in Fig. 1(c). One can observe that for all studied networks just maximal values of betweenness differ. The reason for this is that for scale-free networks, node betweenness is strongly correlated with node degree [32].

### 3. Information flow model

In the information flow model all nodes are treated as both hosts and routers. Each node has a predefined maximum packet routing capacity  $C$  and communication channels have an infinite capacity to transmit the packets. If packets arrive to the node whose routing capacity has been already reached (i.e., congested node), they will be dropped. The dynamics of the model is as follows. At each time step  $t$ , an information packet is created at random node with probability  $p$ . Therefore  $p$  is the control parameter: small values of  $p$  correspond to the flow rate of packets and high values of  $p$  correspond to the high rate of packets. When a new packet is created, a destination node, different from the origin, is chosen randomly in the network. In this paper, we analyze the case that each node is able to send one packet at each time step. The travel time  $T$  of a packet is defined as the time spent by the packet between its source and destination. Here we do not take into account the time delay of data transfer at each node or link, so that all data

are delivered in a unit time, regardless of the distance between any two nodes. Thus, during the following time steps  $t+1, t+2, \dots, t+T$ , the packet travels toward its destination and time  $T$  is related to the path length (the path length is defined as the number of links that transmit the packets). Once the packet reaches the destination node, it is delivered and disappears from the network.

When the amount of packets is small, the network is able to deliver all the packets that are generated. Conversely, when  $p$  is large enough the number of generated packets is larger than the number of packets that the network can manage to solve and the nodes enter in a state of congestion. The characteristic that measures the system performance is the packet drop probability  $\eta$ ,

$$\eta = \frac{R_d}{R} \quad (2)$$

defined as ratio of the total number of deleted packets  $R_d$  and the total number of generated packets  $R$ . A high drop probability indicates that a large percentage of packets cannot reach their destinations. Then, the quality of service is poorer.

## 4. Routes to performance improvement

### 4.1. Static routing

Packets can be delivered according to different routing strategies. When static weighted routing strategy is used, packets choose the routing path with the minimum sum weight of links. As for any pair of source and destination, there may be several paths with the same weight between them. We can randomly choose one of these paths and put it into the fixed routing table which is followed by all packets. It has been assumed that each node has the same capability of delivering packets, that is, at each time step all the nodes can deliver at most  $C$  packets one step toward their destinations according to the fixed routing table. Here we compare two routing strategies: (i) the shortest path routing, i.e., the links in the network have the same weight,  $w_{st} = 1$ , where  $w_{st}$  is weight of link going from  $s$  to  $t$ . Routing communication along the shortest paths is of course beneficial for speed, but if there is a limit to the node load and network traffic is heavy, congestion is a threat to the nodes with the largest betweenness. Obviously, bypassing high-degree nodes, packet will have more chance to reach its destination. (ii) In the second routing strategy weight of the link between the nodes  $s$  and  $t$  is defined as [5]:

$$w_{st} = \left( \frac{k_s + k_t}{\min_{i \neq j} (k_i + k_j)} \right)^\beta, \quad (3)$$

where  $k_i$  denotes degree of node  $i$  and  $\beta$  is an adjustable parameter. The efficient path between nodes  $i$  and  $j$  is corresponding to the route that makes the sum weight of links minimum. As for any pair of source and destination, there may be several efficient paths between them. We randomly choose one of them and put it into the fixed routing table which is followed by all the information packets.

In Fig. 2(a), we show the betweenness deviation as a function of  $\beta$  on different scale-free networks. The optimal routing strategy for generic scale free network and scale free network on lattice is corresponding to  $\beta_{opt} = 1 \pm 0.1$ , where betweenness deviation is the smallest. This is also optima value for NREN of the Netherlands. The optimal value for French NREN is higher, i.e.,  $\beta_{opt} = 1.2 \pm 0.1$ , due to larger betweenness deviation. Obviously  $\beta = 0$  recovers the shortest path length. In comparison with the shortest path routing strategy average path length slightly increases with  $\beta$ , cf. Fig. 2(b).

### 4.2. Dynamic routing

In this paper we also analyze the effectiveness of the dynamic deflection routing strategy. We assume each node has a knowledge about the load of its neighbors. If a package is about to arrive to a congested node, it will be deflected, i.e., its path will be dynamically extended. In other words, if we denote path between nodes  $i$  and  $j$  as  $P(i \rightarrow j) := x_0, x_1, \dots, x_{n-1}, x_n$ , where  $x_0 = i$  and  $x_n = j$ . The node  $x_m$ , instead forwarding package to the congested node  $x_{m+1}$ , deflects the packet back to the node  $x_{m-1}$ . In the moment  $t+1$ , the node  $x_{m-1}$  sends the packet to the node  $x_m$ , and in the moment  $t+2$  the packet is sent to the node  $x_{m+1}$ . The deflection of the packet is tried only once.

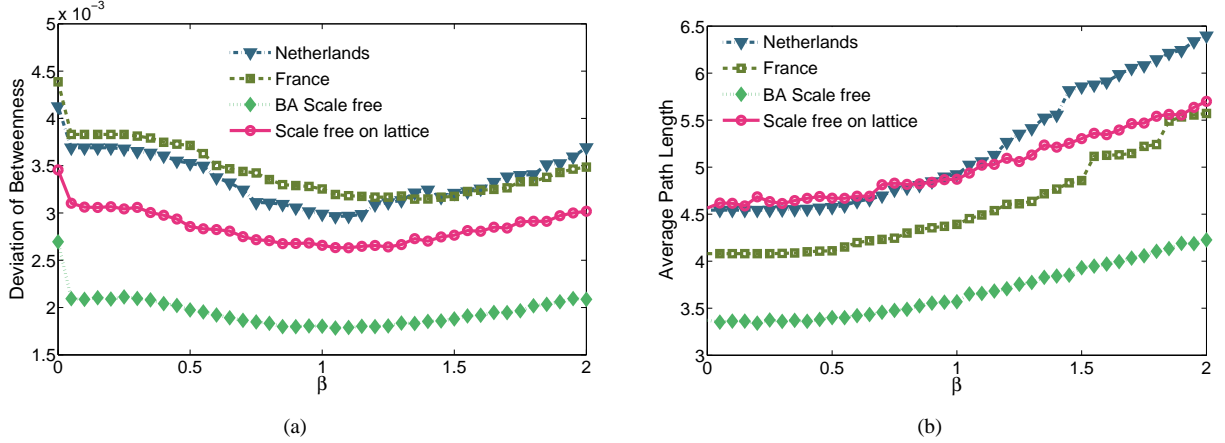


Figure 2: (a) Deviation of node betweenness vs  $\beta$  and (b) average path length vs  $\beta$  for different network models.

In order to avoid a reduction of the system performance due to the deflection traffic, we introduce an average expected load of the node  $i$   $q_i = b_i N p$ , and a condition that the node  $i$  can send packet back only if  $q_i < 0.5C$ . The localized congestion events are more likely to occur at the nodes with higher betweenness and that in the regime when traffic is not heavily congested. We find that it is sufficient to implement the deflection routing only in the nodes with highest betweenness (about 10% of all nodes, i.e., six nodes in our systems). A higher amount of the nodes with deflection routing capability does not improve significantly the network performance.

## 5. Simulation results

To compare different routing strategies, we apply the routing algorithms to the two generic networks and NRENs of France and the Netherlands and measure packet drop probability  $\eta$ . As shown in Fig. 3, the scale-free network on lattice under the shortest path routing strategy reproduces well behavior of both NREN topologies, for both simulated node transfer capacities  $C = 2$  and 4. We can see that in real-world networks and scale free network on lattice for  $p > 0.1$  and for node capacity  $C = 2$  more than 40% of generated packets is deleted. Also, when amount of the traffic in the network is small ( $p < 0.1$ ), there is significant amount of loss, i.e., more than 5%. The BA scale free network is less prone to congestion compare to the scale-free network on lattice and two NRENs, which is in good agreement with the fact that this network has shorter average path length. For the higher node transfer capacity ( $C = 4$ ) number of deleted packets significantly decreases and there are almost no lost packets for small traffic.

An improvement static and dynamic routing strategies is analyzed in Fig. 4 and Fig. 5, respectively. They confirm that the static weighted routing using the topological information can greatly improve the traffic flow for small  $p$  values, in comparison with the shortest path routing mechanism in the scale-free networks. The weighted routing method proves to be better for NREN topologies and SFL network. The dynamic routing strategy is better in case of BA scale free networks also due to the shorter paths, cf. Fig. 5. The shorter paths between nodes result in a lower amount of the packages being transferred through the network at any instance of time, allowing for the dynamic deflection algorithm to be more efficient.

The dynamic and static routing strategies are complementary and can be combined to reduce package drop rates. The system performance for combined static and dynamic routing and the static routing is compared in Fig. 6. The redistribution of the traffic load from most congested nodes enables more efficient the dynamic deflection routing. Improvement is in range from 5% – 20%. The generic scale free network on lattice and French NREN showed the largest improvement. The reason for this is the local connectivity structure around most congested nodes and proximity of the other also congested nodes. For example, in NREN of Netherlands four most congested nodes after path redistribution where in the proximity.

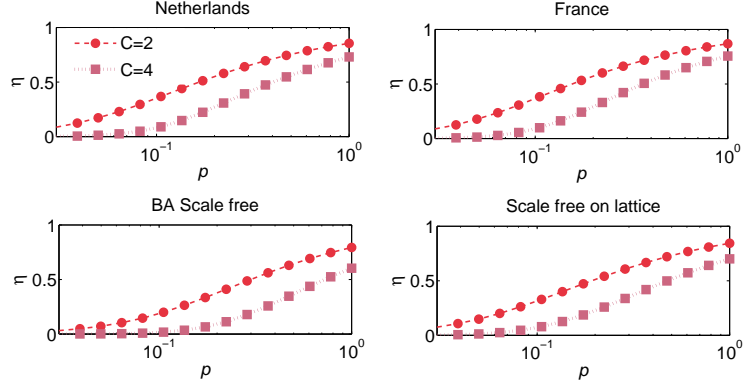


Figure 3: Package drop probability  $\eta$  vs. the packet-generating rate  $p$  for the shortest path routing algorithm.

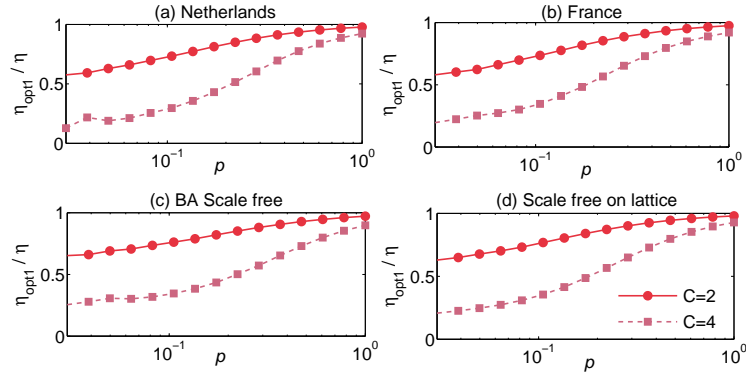


Figure 4: Comparison between parameter  $\eta$  as a function of packet-generating rate  $p$  for the shortest path routing and static weighted routing strategy with  $\beta_{opt}$  ( $\eta_{opt1}$ ).

## 6. Conclusions

In summary, we have introduced a information flow model for networks without buffering capacity. The point of the network jamming and amount of information lost depends on the underlying network structure. We have shown that scale free model on lattice reproduces well both topological and information transport network characteristics of national research and educational networks of the Netherlands and France. We have further described a dynamic deflection routing strategy suitable for networks without buffers. The proposed strategy dynamically extends package path before it reaches a congested node. We show that the dynamic deflection routing can further increase network information transport capacity when combined with the static efficient routing strategy.

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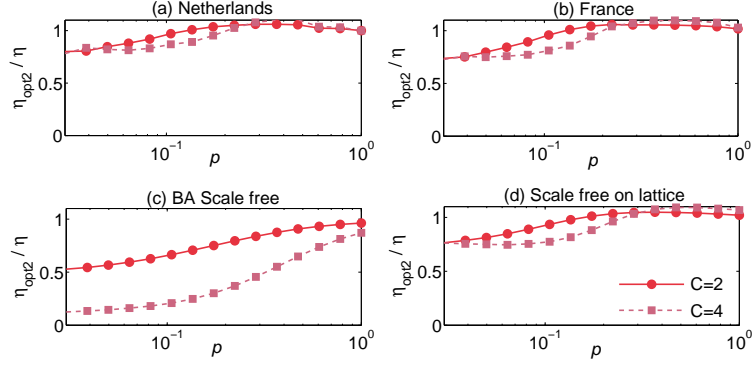


Figure 5: Comparison between parameter  $\eta$  as a function of packet-generating rate  $p$  for the shortest path routing and dynamic routing algorithm ( $\eta_{opt2}$ ).

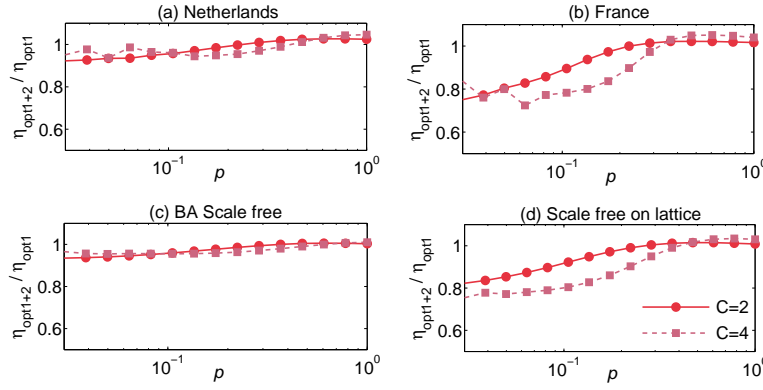


Figure 6: Comparison between parameter  $\eta$  as a function of packet-generating rate  $p$  for static weighted routing strategy,  $\beta_{opt}$  ( $\eta_{opt1}$ ) and combined static and dynamic routing ( $\eta_{opt1+2}$ ).

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